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Applying Overt Systems Thinking to the Design of the Femtosource

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Topics

- Key principles of "systems thinking" for designing the femtosource
- Defining the femtosource trade space
- Mathematical formulation of the design problem
  - ☞ Limitations and complications
- Some simplified equations for insight into the femtosource trade space
- Identifying injector-gun alternatives
- Preliminary evaluation of Risk Vs. Performance for the Cs_2Te cathode
- The DoE model of a project life-cycle
- The next step?

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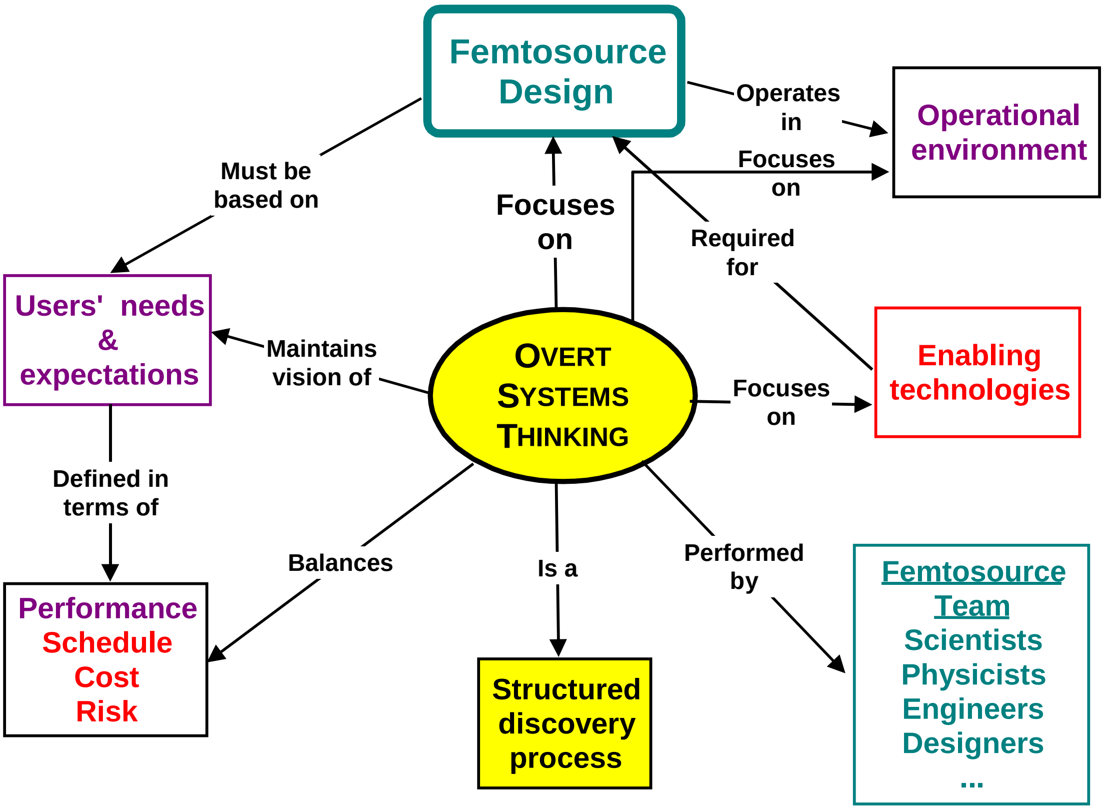
Key Principles of Systems Thinking for the Femtosource



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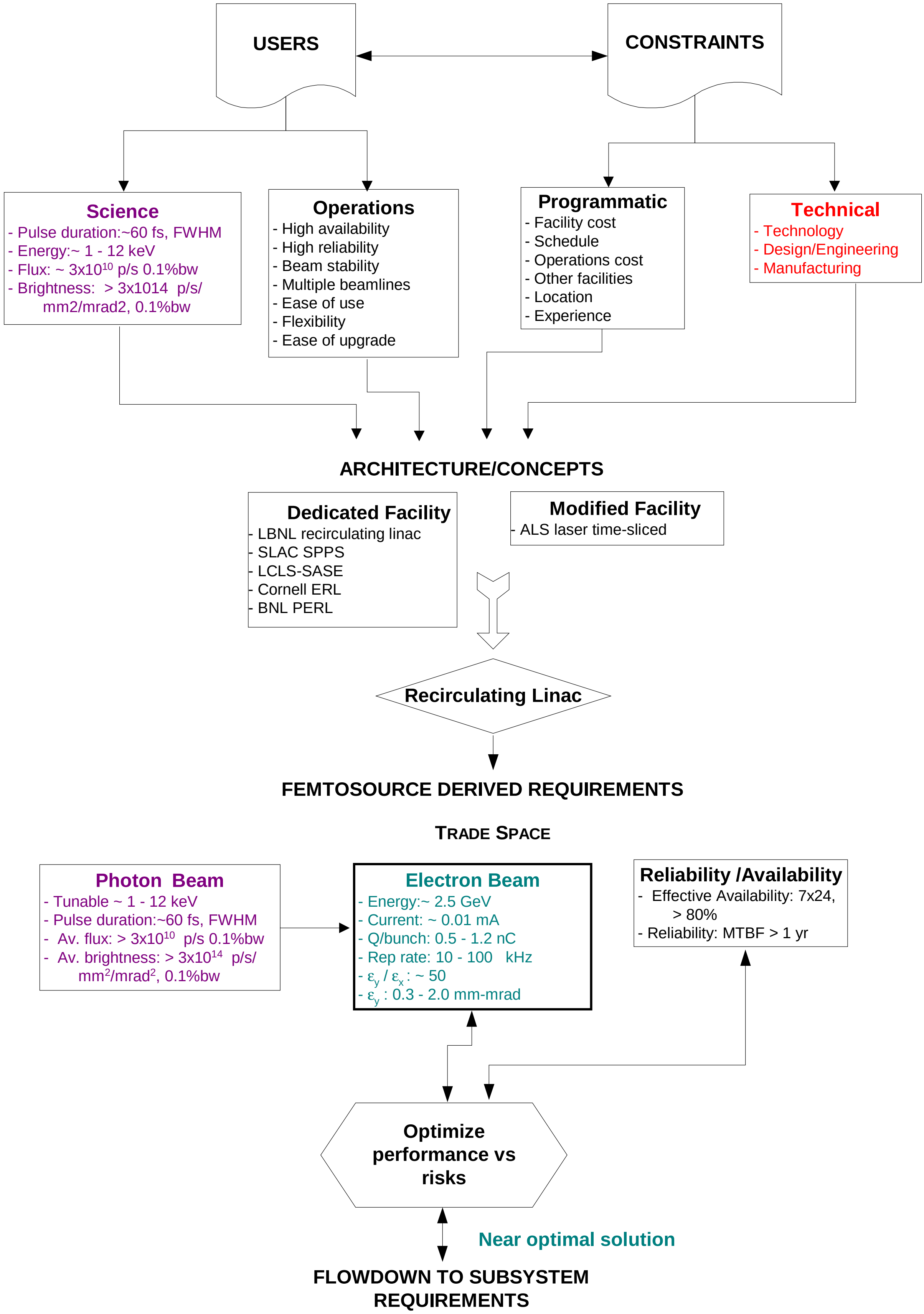
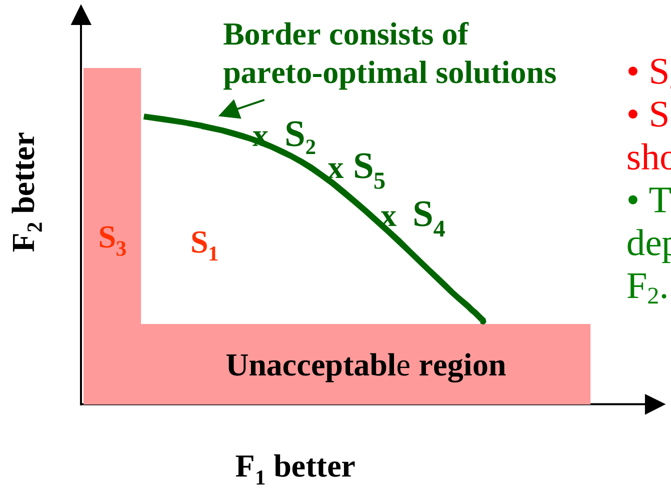
Defining the Femtosource Trade Space



Mathematical Formulation of the Design Problem

✓ Simultaneously optimize several possibly conflicting criteria given by functions $\{F_1, F_2, \ldots, F_n\}$ that depend on the design variables $\{x_1, .., x_k\}$ and are subject to the constraints, $\{C_1, \ldots, C_m\}$.

☞ **This is formally nice, but there may not be a dominant solution! Also system design is an NP-complete problem!**



- S_3 is not an acceptable solution
- S_1 is not a pareto-optimal solution and should not be given further consideration
- The selection among S_2, S_4, and S_5 depends on the relative importance of F_1 and F_2.

It is important and simple (but not easy) to achieve a "near optimal" design given a feasible design!

Some Simplified Models for Insight into the Design Trade Space

Notes:

- Color code

XXX: Technology constraint
YYY: Science driver
ZZZ: Design trade

- **Use of natural units.**

1. **Cathode Emittance** (C. Sinclair)
   $Q_b \le Q_{stored} / 10$: To avoid space charge problems

   ➢ ε_n **[mm-mrad] >= {(Q$_b$[pC] /111*EF$_{cath}$[MV/m])*E$_{thermal}$[51 meV])}$^{1/2}$**

To achieve lower emittance:

- ✓ Design photocathode and gun cavity with
  -Lower characteristic energy of emitted e^-'s, $E_{thermal}$
  -Higher E-field at cathode, EF_{cath}
- ✓ Reduce charge per bunch, Q_b

2. **Photoinjector Laser Power, P_{laser}** (C. Sinclair)

➢ **P_{laser}[W] >= (Q_b[mC]*R_r[/sec])*(124/λ_{laser}[nm])/ QE[%]**

To require lower laser power:

- ✓ Use cathode with higher quantum efficiency, QE
- ✓ Use cathode with lower operating wavelength, λ_{laser}
- ✓ Reduce Q_b
- ✓ Reduce repetition rate, R_r

3. **Flux, S_n** (LBNL X-Ray Data Booklet)

   ➢ **ε_n[keV] = 0.95*n*E_b^2[GeV]/(1 + K^2/2) *λ_u [cm]**

   ➢ **S_n[ph/s-0.1% bw] = (1.431*10^{14})*N_u*Q_n(K)* Q_b[C]*R_r[/sec]**

   K = 0.934*λ_u [cm] *B_0[T]

To achieve higher flux:

- ✓ Design higher performance undulator (B_0, λ_u, Nu)
- ✓ Design machine with higher beam current (Q_b, R_r)

To achieve different photon energies:

- ✓ Select beam energy, E_b
- ✓ Select and tune undulator parameters
- ✓ Use higher-order harmonics, n

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4. Peak Brightness (LBNL X-Ray Data Booklet)

➢ $B_n(0,0)$ [ph/s/mm^2/mrad^2 0.1% bw] $= S_n/\{(2\pi)^2\, \sigma_{Tx} * \sigma_{Ty} * \sigma_{Tx'} * \sigma_{Ty'}\}$

$\sigma_{Tx} = \{\sigma_x^2 + \sigma_r^2\}^{1/2}$; $\sigma_{Tx'} = \{\sigma_{x'}^2 + \sigma_{r'}^2\}^{1/2}$

$\sigma_{r'} = (\lambda_n * L_u)^{1/2}$; $\sigma_r = (\lambda_n / L_u)^{1/2}$

To achieve higher brightness:

- ✓ Increase flux
- ✓ Reduce beam sizes, σ_{Tx} and σ_{Ty}
- ✓ Reduce beam divergences, $\sigma_{Tx'}$ and $\sigma_{Ty'}$

5. Pulse Length, σ_z (A. Zholents et al.)

$\sigma_z >= (E_b / eU * k_{rf}) * \sigma_{y'}^{rf} * \{1 + (\sigma_r/\sigma_y)^2\}^{1/2}$

$\sigma_z >= (E_b / eU * k_{rf}) * \sigma_{y'}^{rf} * \{1 + (\sigma_{r'}/\sigma_{y'})^2\}^{1/2}$

To achieve lower pulse duration:

- ✓ Reduce the vertical angular size of the e-beam in the deflecting cavity, $\sigma_{y'}^{rf}$
- ✓ Increase the RF deflection voltage, eU
- ✓ Increase the RF wave number (frequency), k_{rf}
- ✓ Reduce the diffraction limited size of the radiation, σ_r

Notes:

- Need to examine the importance of the corrections and/or use more accurate equations where necessary.

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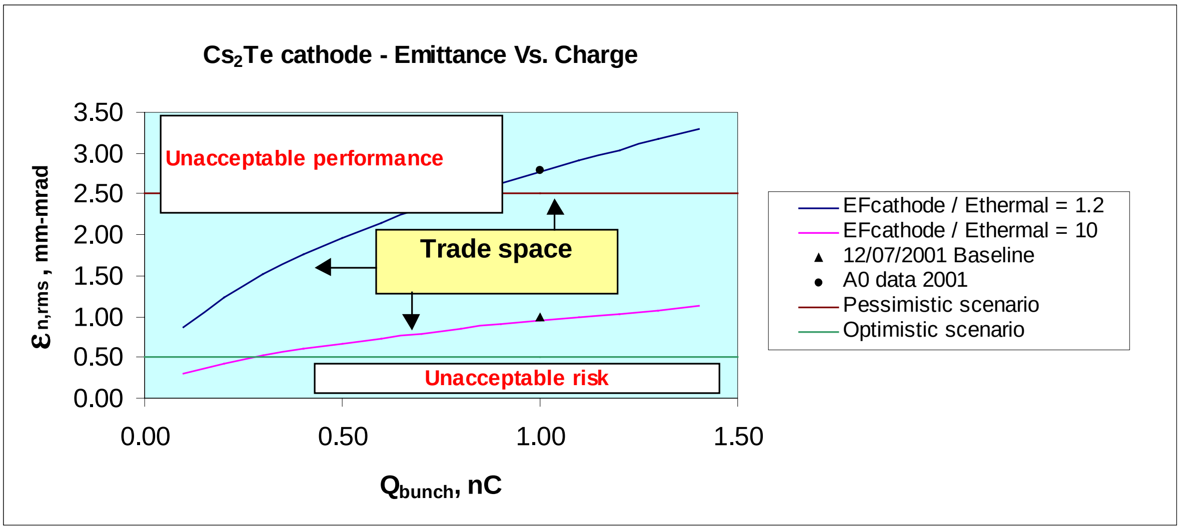
Trade Studies: Injector cathode & laser
Leading Photocathode Alternatives

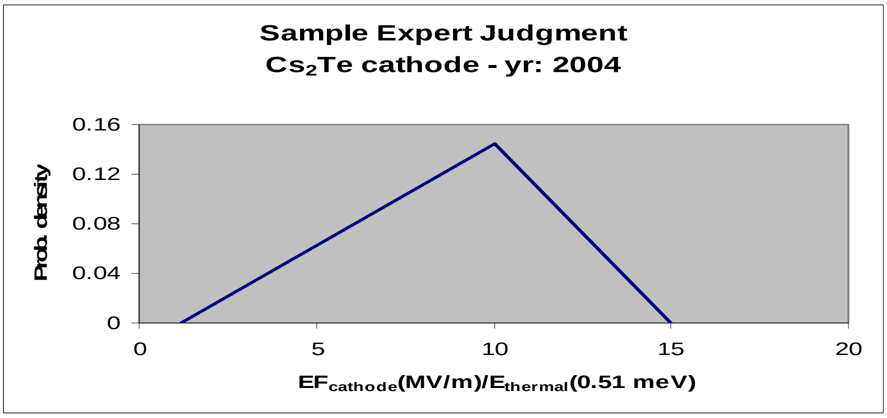
	RF Guns		DC Guns	
Criteria	**Metal**	**$Cs_2Te^{\&+}$**	**GaAs**	**CsSb**
Projected Q_{bunch}, nC +	1.0	1.0	1.0	
I, mA+	0.01	0.01	0.01	
Normalized emittance, measured @1nC, mm-mr	?	2.8	?	
Projected normalized emittance, mm-mr@1nC+	1.0	1.0	1.0	
$E_{thermal}$, β(51 meV = 300^0K)	?	6.0	1.2	
EF_{cath}, measured, MV/m	?	35 - 40	10 - 20	
Projected EF_{cath}, MV/m +	?	54.1	10.8	
P*Qe, W-%	0.0045	0.0045	0.0015	
Best Qe, measured, %		24 @ prep		14@ start
Projected life, years	years	years*	years^	Low@
Projected Qe, lifetime, %	0.01	1.0	10.0	
Lifetime limiting factors	Heat removal	Coating, Ion bombardment,…	Ion bombardment	
Needed improvements	Preparation technique	Preparation technique	- Field emission effects - DC power supply	
Probability of success / Confidence level	Medium	High/Medium	Medium	
Design complexity	- High vacuum	- High E_{cath} - Low ε	- Very high vacuum	
Laser power, mW	450.0	4.5	0.15	
Laser sources	UV	UV below ~ 275nm	780nm	
Laser risk	Medium	Low	Low	
Comments	Not actively pursued by others because of low Q_e.	1st choice: Tesla	- Jefferson Lab - PERL fallback	PERL studies
Conclusion ?	**1st backup**	**Baseline**	**Open**	**Drop!**

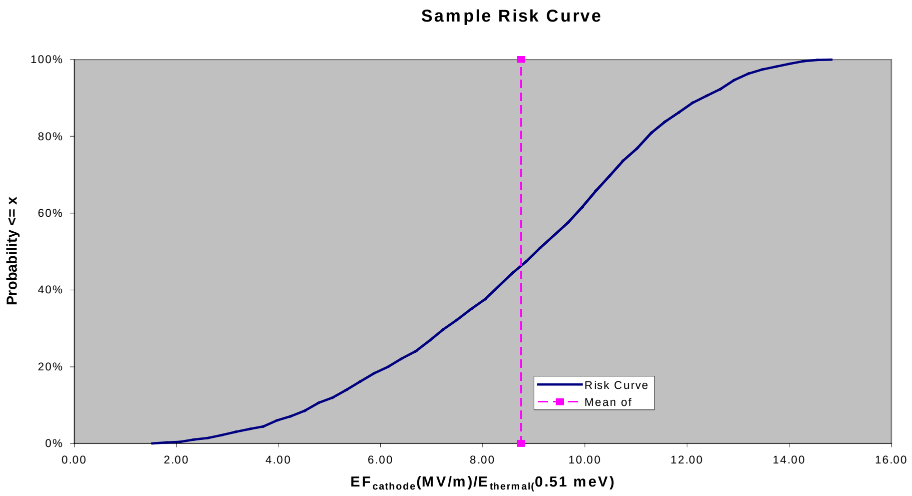
+ Femtosource Advisory Committee Meeting 12/7/01
& Use of A0 Photoinjector data
** Based on QE of 2% for 200 mA after 1 year.*
^Based on lifetime of 10^5 C/cm^2 for DC gun.
Scaled from 5 hours for a cathode spot size of 1 mm radius and 200 mA current.
@ Lifetime decays exponentially. 2.3 hrs to Qe of 1% demonstrated in 1992.

Cs_2Te Cathode - Risk Vs. Performance

- ε_n [mm-mrad] >= $\{(Q_b[pC] / 111 * EF_{cath}[MV/m]) * E_{thermal}[51\ meV])\}^{1/2}$







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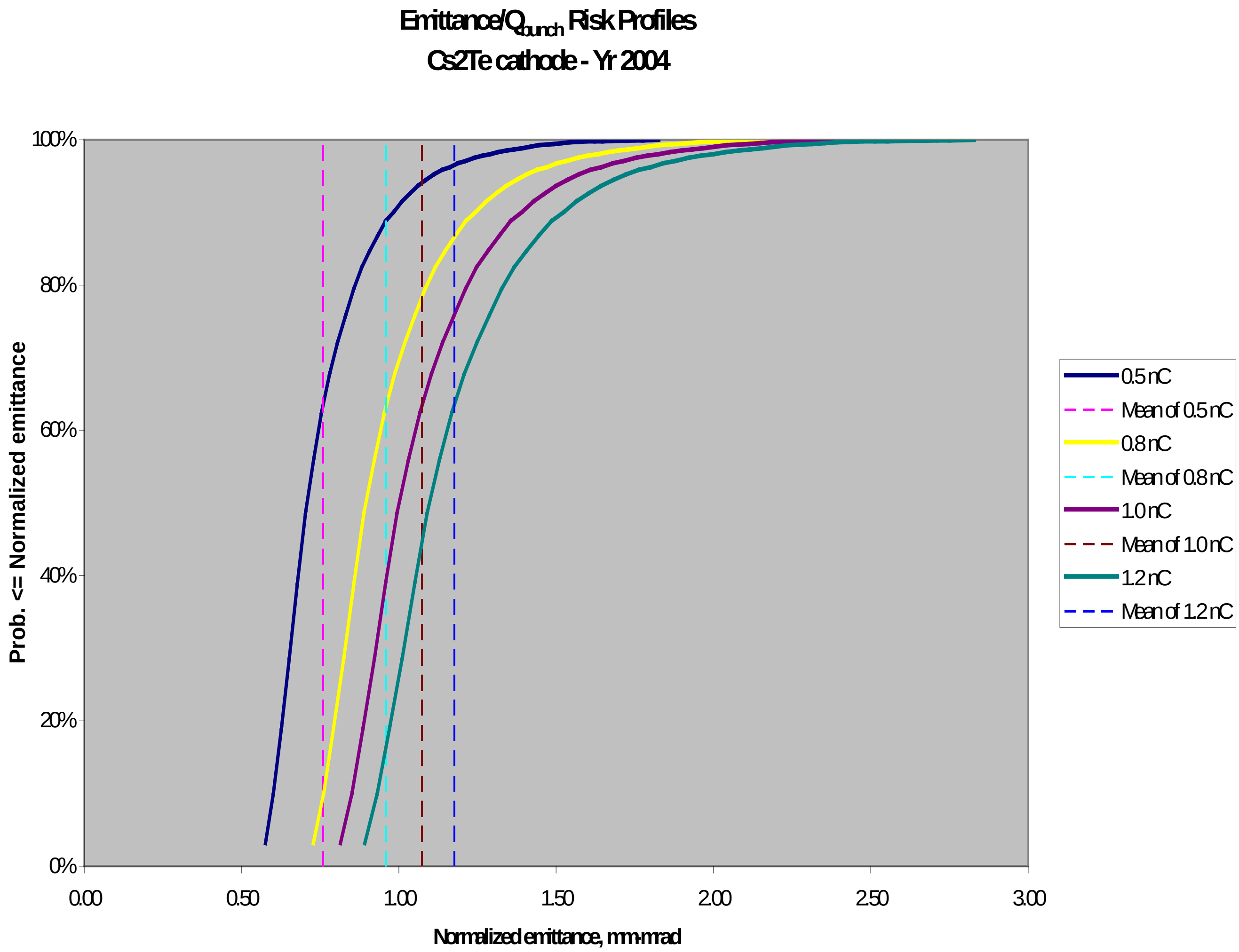
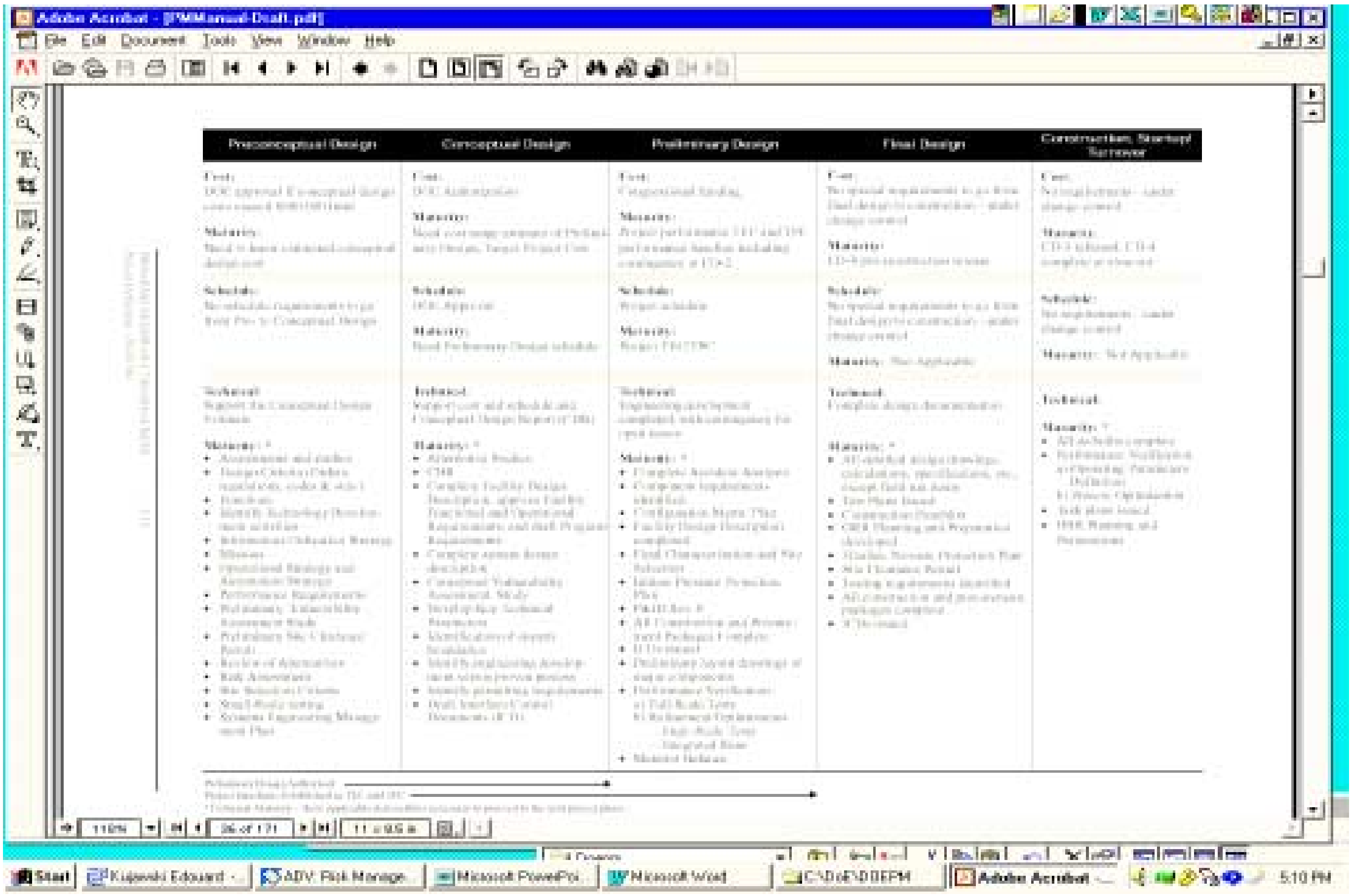


☞ Some Important Questions We Can Address

- What is the impact on technical performance and risk of proceeding with a 1.2 nC / bunch Cs_2Te design?
- What Q_{bunch} gives a >= 80% of probability of achieving an emittance <= 1.0 mm-mrad in the near future?
- Others?

Typical DoE Project Life-Cycle



- ~ 80 to 90% of the development cost of a large system is predetermined by the time 5 to 10% of the development effort has been completed!
- Effort in the study phase results in significant benefits and payback.

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